

HAMPTON UNIVERSITY



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Spaceborne Photonics Institute FINAL TECHNICAL REPORT

HAMPTON UNIVERSITY
DEPARTMENT OF PHYSICS

NATIONAL AERONAUTICS
AND SPACE ADMINISTRATION
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July 1994

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Spaceborne Photonics Institute **FINAL TECHNICAL REPORT**

July 1994

National Aeronautics and Space Adminis-
tration
NAG-1-1091

Hampton University
Hampton, VA 23668

Principal Investigators

D. D. Venable
U. O. Farrukh
K. S. Han
I. H. Hwang
N. W. Jalufka
C. W. Lowe
B. M. Tabibi
C. J. Lee

Other Contributing Authors

D. Lyons
A. Maclin

Adequate reports have been written in association with this grant in the past. The Spaceborne Photonics Institute was established to develop a sustained research effort at Hampton University in the area of optical physics. One of the principal objectives was to establish adequate research expertise to initiate a Ph.D. program in physics. The grant funding the Spaceborne Photonics Institute (SPI) was the first such grant received by the Physics Department for this purpose and was instrumental in the University's decision to

move forward with the physics doctoral program. The table below shows the chronology of events that have led to the Ph.D. Physics program.

Ph. D. Program Development Chronology

April 1984	Physics department's Program Plans indicate that it would begin feasibility study on offering the Ph. D.
October 1986	Feasibility plan submitted to Dean of Pure and Applied Sciences
April 4, 1989	Report submitted to President Harvey on Ph. D. in Physics
April 28, 1989	Report submitted to Board of Trustees; Trustees approved three year implementation plan
January 1990	Degree plan submitted to Graduate Council
January 1990	Spaceborne Photonics Institute funded (@ \$1.9 M for 3 years)
March 1990	University Ph. D. Advisory Committee established by President Harvey
April 6, 1990	First external consultant visits campus and reviews program drafts
May 2, 1990	External review team visits campus
May 30, 1990	SCHEV representative visits department
April 23, 1991	Draft of application sent to SCHEV representative
August 1991	Response to draft application received from SCHEV representative
September 1991	NuHEP Funded (@ \$5 M for 5 years)
October 1991	Final SCHEV application developed

November 1991	RCOP Funded (@ \$8.5 M for 5 years)
November 1991	Notification submitted to SACS of intent to offer program
November 1991	Application submitted to SCHEV for degree escalation
February 1992	SACS Prospectus submitted
May 1992	Accreditation site visit by SCHEV
June 1992	SCHEV authorizes student enrollment in doctoral program
June 1992	SACS approves Candidacy for Level V Accreditation
September 1992	First students enrolled in doctoral program
January 1993	First qualifying examination offered
June 1993	SCHEV's conditional approval obtained
September 1993	SACS site visit
December 1993	SACS approves full Level V Accreditation
April 1994	Notification received of Title III funding to strengthen Ph.D. in Physics program, operating support (@1.75M for 5 years)
May 1994	Final Follow-up Report submitted to SCHEV
June 1994	Full accreditation received from SCHEV to confer Ph.D. degree in physics received.

Currently the Ph.D. Program enrolls about 30 students. The majority of these students are from underrepresented minority groups. Students and faculty associated with SPI were phased into the Research Center for Optical Physics (RCOP)

over the past two years. RCOP was funded by NASA as a direct follow on of the efforts of SPI. The same principal investigators involved in SPI were the authors of the RCOP proposal and have continued their research efforts within the new Center. In addition to the RCOP grant, several other major grants have been funded in this area of research. The table below summarizes effort in obtaining additional funds to continue the work of SPI and to continue the growth of the Ph.D. physics program.

Review of Support for SPI/RCOP Related Research

Title	Agency	PI(s)	Amount
Development of Advanced Thermal and Electrical Propulsion System (Instrn.)	DOD/AFOSR	BMT	\$431,656
Thermal-Electrical propulsion with Magneto-Plasma Dynamic Acceleration	DOD/AFOSR	BMT	\$632,204
Microwave Radiation	Army	UOF	\$25,000
ONR-HBCU Summer Faculty Fellowship Program	ONR	AM	\$2,700,000
Fiber Optics Sensors and Smart Materials	NSF	AM	\$300,000
Optical Imaging System	NASA/LaRC	DDV	\$75,000

The executive summary from RCOP given below clearly shows the out-

growth of the efforts of SPI and the related Ph.D. in physics program:

The Research Center for Optical Physics (RCOP) was established at Hampton University in February, 1992 through the Minority University and Education Program at NASA Headquarters. The intent and objectives of the proposal are to : (1) engage in relevant and substantive research of interest to the National Aeronautics and Space Administration and (2) to increase the pool of research scientists and engineers who can help meet the nation's and NASA's manpower needs.

Currently, the annual budget for the RCOP Program is \$2M per year. The principal investigators are actively seeking other federal and private funds to support the research initiatives of the Center and the graduate students involved in the research. We expect that the RCOP faculty will be able to attract other funding at the level of approximately \$1-2 M per year over the long term to sustain and increase the efforts established through the NASA grant.

The impact of RCOP on the educational goals of both the Department of Physics and the University's commitment to technical careers for minority students can not be understated.

The goals of the new Ph.D. program in physics at Hampton University are (a) to establish a research oriented environment in which students may study advanced topics in physics beyond the Master's level, participate in state-of-the-art-research and pursue original ideas and concepts that contribute to the body of knowledge in physics; (b) to provide a source of scientifically and technology trained personnel for local state and national needs; and (c) to

significantly impact the number of underrepresented minorities with advanced degrees in physics. These goals will be accomplished by offering a sound academic program in physics utilizing the expertise of the existing faculty, the addition of new faculty, and the use of adjunct faculty in specialty areas. The research component of the program will utilize existing research facilities in the physics department and the new research facilities currently under construction at the University was occupied in January, 1993. The research efforts established through RCOP will allow Hampton University to achieve these goals in a definitive manner.

The projected impact of RCOP will be measured by the number of highly trained minority students who receive advanced degrees in fields of optical physics over the next 3-5 years. There are currently 17 graduate students involved in the activities of RCOP and 2 undergraduate students. Ten of these students come from underrepresented minority groups in fields of science and engineering. Four of the students are women--3 African American and one American Indian. Of the two undergraduates, both are male and one is African American and the other is American Indian.

Through an aggressive recruitment campaign that is currently underway, we expect to dramatically increase the number of underrepresented minority students who will be participating in the graduate program in optical physics at Hampton University over the next 2-3 years. We expect that an additional five African American students will enroll in the graduate optical physics program by September, 1993 and an additional 5 students by the Fall of 1994. We foresee that the graduate enrollment for RCOP will level off at about 25 graduate students and about 10 ad-

vanced undergraduates students by September, 1994. The first class of Ph.Ds from the RCOP program will probably occur during the calendar year 1995.

The RCOP program is central to the strategic planning process that is currently underway at Hampton University. The physics department at the University has consistently been the leader in obtaining research funds, developing minority students with good technical background that allowed them to be competitive in the global marketplace and is currently the first and only department at the University to offer the Ph.D. degree. As a part of the strategic plan for the University, other departments at the university will develop model programs such as those in physics which will catapult the entire University community into the 21st Century.

The goals and objectives of RCOP and those of NASA and MUREP that were exemplified through the initiative to establish Research Centers of Excellence at HBCUs demonstrate an extraordinary opportunity to develop partnerships between government, universities and industries. It the goal and intent of Hampton University to develop reciprocal partnerships with other government agencies, universities and private industries that will provide the most promising research opportunities for our graduate students and faculty and that will ensure self sufficiency of the Center within the next five years.

The purpose of the Research Center for Optical Physics at Hampton University is to develop a "world class" research center in optical physics that will substantially increase the number of underrepresented minorities who receive the Ph.D. degree in areas of optical physics. The long range goals are to establish state of

the art facilities in spectroscopy, a ground based LIDAR/DIAL systems and a laboratory for both modeling and fabricating optical communications devices using novel fiber materials. The long term goal is to graduate underrepresented minority students with advanced degrees in areas of optical physics.

The technical efforts of the SPI principal investigators and students who continued their work in RCOP were summarized in a recent RCOP report as given below in the listing of publications and presentations:

Usamah Farrukh and Philip Brockman, Temperature Distribution in end-pumped Crystal Laser Rods: Transient and Spatial Variation, Accepted for Publications, Appl. Optic (1992).

In Hwang and W. Meador, An Analytical Model for Longitudinally Pumped Continuous-Wave Lasers, J. Appl. Phys. 72(7) 2556-2561 (1992).

Chang Lee and In Hwang A Model for CW Multi-doped Solid State Lasers, Submitted to IEEE J. Quantum Electronics, MS # 8100, 1992.

Yong S. Cho*, In Hwang and K.S. Han, Amplified Emission in Solar-Pumped Iodine Lases. Proceedings of the International Conference on Lasers 91, P. 181, (1992).

Chang J. Lee, and In Hwang, A Model for Diode Pumped Multi-doped Solid State Laser, submitted to IEEE J. Quantum Electronics (1992)

Yong S. Cho*, In Hwang and Kwang S. Han, Amplified Spontaneous Emission in Solar-Pumped Iodine Lasers, Proceedings of the International Conference on Lasers, 1991, p. 182 (1992).

U. O. Farrukh, M. F. Clayton* and P. Brockman, Thermal Lensing in End-Pumped Laser Rods When Pumped by Dual Pulse Sequences, OSA Annual/ILS '92 Meeting, TuF3, September 20-25, 1992, Albuquerque, NM

U. O. Farrukh and N. P. Barnes, Time-dependent Birefringence in End-Pumped Uniaxial Crystals, OSA Annual/ILS '92 Meeting, TuF4, September 20-25, 1992, Albuquerque, NM

In H. Hwang, An Analytical Model for End Pumped CW Solid State Lasers, OSA/ILS-VIII Conference, September 20-25, 1992, Albuquerque, NM.

Y.K. Kim*, K.S. Han and Ja H. Lee, Comparative Study of IN-PIStron and Spark Gap, 1992 Power Modulator Symposium, Conference Record 92CH3180-7, p. 402, June 23-25, 1992.

B. Kim*, K.S. Han and J. H. Lee, Hypocycloidal Pinch (HCP) Light Source for Tm³⁺: YLF Excitation, 1992 IEEE Plasma Science Conference, Conference Record 92TH0460-6 3P7, p. 132, June 1-3, 1992, Tempe, Florida.

Chang Lee, Gyoowan Han*, C. H. Bair, N. P. Barnes and R. V. Hess, Dependence of Alexandrite Laser Pumped 2.1 micron Laser Performance on Pumped Pulselength, Presented at the OSA Annual /ILS '92 Meeting, September, 1992, Albuquerque, NM.

Chang J. Lee, Gyoowan Han*, C. H. Bair, N. P. Barnes, P. Brockman and R. V. Hess, Alexandrite Laser Pumped Ho: Tm:YLF Laser Performance, Accepted for Advanced Solid-State Laser Conference, February, 1993, New Orleans, Louisiana.

Bagher M. Tabibi, A 30-W CW Solar Simulator-Pumped Iodine, CLEO QELS Conference, May 10-15, 1992, Anaheim, California.

Charles Terrell* and Bagher Tabibi, CW Iodine Laser Performance of t-C₄F₉I Under Closely-Simulated AMO Solar Pumped, The 59th Meeting of the Southeastern Section of APS, November 12-14, 1992, Oak Ridge, TN.

Bagher M. Tabibi, A 30-W CW Solar Simulator-Pumped Iodine, CLEO QELS Conference, May 10-15, 1992, Anaheim, California.

SPI had seven co-principal investigators and four faculty associates. Brief resumes of the faculty participants follow:

Dr. Demetrius Venable is the director and principal investigator of SPI and RCOP. He has held prior positions at the university serving as professor and chairman of physics, Dean of the graduate school and currently Vice President for Research. He has more than 16 years of service to Hampton university and holds a Ph.D. degree in physics from American University and is an African American.

Dr. Usamah O. Farrukh is a co-principal investigator of SPI/RCOP and associate professor of electrical engineering. His research interests are laser system modeling, laser propagation and optical systems.

He has seven years of service at Hampton University. He received his Ph.D. degree in electrical engineering from the University of Southern California and is an Arab American.

Dr. Kwang Han is a co-principal investigator of SPI and professor of physics. His research interests are in plasma and laser physics. He has more than 27 years of service at Hampton University. He received his Ph.D. degree in physics from the College of William and Mary and is an Asian American.

Dr. In H. Hwang is a co-principal investigator of SPI/RCOP and associate professor of physics. His research interest is diode-pumped solid state lasers. He has five years of service at Hampton University. He received his Ph.D. degree in physics from the Korean Advanced Institute of Science and Technology and is an Asian resident alien.

Dr. Nelson Jalufka is a co-principal investigator for SPI/RCOP and professor of physics. His research interests are in atomic and molecular spectroscopy and laser physics. He has three years of service at Hampton University. He received his Ph.D. degree in physics from the University of Colorado and is a white American.

Dr. Bagher Tabibi is a co-principal investigator of SPI/RCOP and associate professor of physics. His research interests are lidar and non-linear optics. He has more than nine years experience at Hampton University. He received his Ph.D. degree in physics from Moscow State University, and he is Asian American.

Dr. Chang Lee was a faculty associate in SPI/RCOP and research assistant professor of physics. His

research interest is optical spectroscopy. He joined the Hampton University Community in May, 1992. He received his Ph.D. degree in physics from Old Dominion University and he is Asian American.

Other faculty members who have joined as a part of the SPI/RCOP initiative are Dr. Arlene Maclin and Dr. Donald Lyons. These persons had their primary responsibilities in achieving the objectives of RCOP.

Participation of students in professional conferences as well as the Technical Review Committee Meeting at Hampton University has been quite active. The following students in SPI/RCOP have made technical presentations in relationship to their work done on SPI and RCOP

Donica Allen-Wells, Lifetime Measurements of Excited Iodine Atoms In perfluoralkyl Iodides.

Edgar Russell, Variations in Ozone Concentration in the Vicinity of Wallops Island.

Trina Veals, Ionized Cluster Beam Deposition of Phtalocyanine and a Microvoid Characteristic Study Using Positron Annihilation Techniques.

Apriel Hodari, 1.06 Micron Diode Pumped Cr: Nd: GSGG Laser - System Setup and Experimentation.

Charles Terell, CW Iodine Laser Performance $t\text{-C}_2\text{F}_9\text{I}$ Under Closely Simulated AMO Solar Pumping.

Several students who were supported under this grant completed Master of Science Theses in Physics:

Donica Allen-Wells, Lifetime Measurements of Excited Iodine Atoms In Perfluor Alkyl Iodides, (December, 1992) Advisor--Dr. Jalufka.

Jaeho Choi, Hard Core Flashlamp Pumped UV Dye Laser, (July, 1992) Advisor--Dr. Han.

Yong Su Cho, The Effects of Amplified Spontaneous Emission On A Solar-Pumped Iodine Laser Amplifier (July, 1992) Advisor--Dr. Hwang.

Marian Clayton, Temperature Distribution in Laser Rods When Pumped by Pulses with Gaussian Time Profiles, (December, 1992) Advisor--Dr. Farrukh.

Bonglea Kim, Hypocycloidal Pinch Light Source for Tm^{3+} : YLF Laser Excitation, (July, 1992). Advisor-- Dr. Hwang.

Jong H. Kim, Plasma Dynamics in Hypocycloidal Devices, (July, 1992) Advisor--Dr. Han.

Yong Ki Kim, Comparative Study of Closing Plasma in Inverse Pinch Switch and Spark Gap, (July, 1992) Advisor--Dr. Han.

Charles Terrell, CW Iodine Laser Performance t-C₂F₉I Under Closely Simulated AMO Solar Pumping, (May, 1993) Advisor--Dr. Tabibi.

Trina Veals, Ionized Cluster Beam Deposition of Phtalocyanine and a Microvoid Characteristic Study Using Positron Annihilation Techniques, (May, 1993)-- Advisor--Dr. Eftekhari at NASA Langley.

Kyongchul Woo, The Conversion Efficiency of Photovoltaic Converters with Pulsed Lasers, (December, 1992) Advisor--Dr. Jalufka

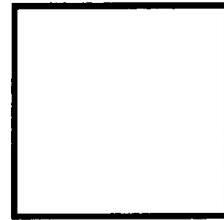
Finally a technical report for SPI is

given in the Appendix to this report to outline the level of reporting presented over the course of the project. This report, written in January 1992, represented the final formal report of SPI prior to the establishment of RCOP. With the initiation of RCOP in February 1992, a new NASA technical oversight committee was created and the directions of the research were changed based on the directives of NASA. In 1992 funds were received from both SPI and RCOP. This was the only year in which funds were received from both projects and it was indicated that 1992 would serve as a phase-out year for SPI and an initiation year for RCOP.

Appendix

Appendix

SPI 1991



Spaceborne Photonics Institute ANNUAL REPORT 1991

**HAMPTON UNIVERSITY
DEPARTMENT OF PHYSICS**

**NATIONAL AERONAUTICS
AND SPACE ADMINISTRATION
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K. S. Han
I. H. Hwang
N. W. Jaflufka
B. M. Tabibi
C. J. Lee

applications, who can significantly contribute to NASA's missions. This entails producing students trained at both the baccalaureate and graduate levels. Typically it is only in graduate school when a student learns to think deeply about a specific research problem and is thus able to make an original contribution to the state of knowledge. Undergraduate students are exposed to this type of research in the hope that the experiences that they receive will motivate them to pursue further studies in NASA related aerospace fields. It is important to note that since Hampton is a Historically Black University, SPI's efforts significantly impact the number of underrepresented minority students in this area.

INTRODUCTION

The Hampton University Spaceborne Photonics Institute (SPI) was formed in 1989 to act as an umbrella for ongoing research in laser systems and materials. The mission of the SPI is to (a) investigate laser systems and new optical materials for space applications such as remote atmospheric sensing, power beaming, communications, optical signal processing and computing and (b) significantly increase the pool of minority scientists trained in these areas. While no limits are placed on the scope of photonics problems that will be eventually considered by the SPI members, we currently focus on "Advanced Photonic Materials", and "Advanced Laser Systems" for spaceborne applications.

One of the principal goals of SPI is to assure that a significant number of persons are trained in NASA related research areas. It is SPI's goal to increase the pool of minority scientists, with expertise in photonics for space

ACTIVITIES FOR 1991

Currently (Fall 1991 Semester) 16 graduate students are being supported under the Spaceborne Photonics Institute. Six of these are new students. The new students are being given assignment at NASA LaRC or on campus. Five students under the Spaceborne Photonics Institute completed requirements for the Master of Science degree during the Spring or Summer terms. Table 1. list the names and thesis titles of these students. Table 2 summarizes the number of students supported for the 1991 year.

SPI played a major role in the sponsorship of the 1991 Annual meeting of the National Society of Black Physicists and the 18th Day of Scientific Lectures held on the University campus April 10-13, 1991. SPI provided resources to held support the publication of the *Proceeding* for that Conference. Approximately 75 paid registrants attended the meeting. William R. Harvey, President of Hampton Univer-

sity, opened the meeting with welcoming remarks on behalf of the University. Twelve members presented papers at the meeting. Dr. James H. Stith, Professor of Physics at West Point Military Academy, served as the Keynote Speaker for the Banquet. Dr. Stith is the first African-American Physicists to be elected as President-Elect of the American Association of Physics Teachers.

SPI researchers participated in the Jet Propulsion Laboratory's Third Annual Technical Interchange Workshop, January 22-25, 1991 in Pasadena, CA. C. W. Lowe and D. D. Venable presented a paper on "Focused Studies in Spaceborne Photonics", where a detailed discussion of SPI and its activities was presented.

Table 1. Master Theses Completed by SPI Students

Smith, Cecily	A Computer Model of the Diffuse Reflectance of LiInSe ₂
Hong, Seung Heon	Comparative Study of Plasma Light Sources for Pumping Titanium Sapphire Laser
Oh, Jaehwan	Growth and Characterization of LiAlSe ₂
Jang, Seog Sue	The Effect of Buffer Gas Helium on the Vibrational Relaxation of Diatomic Bismuth
Gambo, Abdulaziz Mohammed	Closely AM0 Solar-Simulated Pumping of Photodissociation Iodine Laser

Table 2. Summary of Student Support 1991

# Students Total	# Degrees Conferred MS
22	5

ACTIVITIES PLANNED FOR 1992

In addition to the research activities discussed below, SPI plans to continue to provide general support for the implementation of the doctoral program in physics at Hampton University. Additionally, the research currently being

conducted under the auspices of SPI will serve as the research core for the implementation of the newly funded Research Center for Optical Physics (RCOP). The proposal for support of RCOP was written by the principal investigators of SPI. This Center has been funded by NASA as a part of its Core Research Program. RCOP will be phased in as SPI is phased out during its last year of operation. All of the goals and objectives currently under effect through SPI will be continued and expanded through RCOP.

SPACEBORNE PHOTONICS INSTITUTE RESEARCH SYNOPSIS

Modelling of Space-Borne Solid-State Laser Systems

Principal Investigator: Usamah O. Farrukh

DESCRIPTION OF RESEARCH

This investigation is designed to develop software code to support the design of the two micrometer solid state lasers. The laser systems are to be incorporated into the design of space based sensor systems. The code should predict transient spatial temperature distribution and use the obtained information to assess the severity of optical thermal lensing and other non linear optical effects.

ACCOMPLISHMENTS

The thermal modelling program has been fully debugged and implemented to obtain temperature distributions in side and end pumped laser crystals. Problems in the performance of the program as was reported previously has been fixed. Data has been obtained for the temperature distribution in laser rods used in NASA Langley experimental systems. The program at the present time has the following features:

- (a) cylindrical laser rods can be handled;
- (b) optical axis along the axis of the rod (uniaxial) or a crystal with cubic symmetry (no optical axis) can be handled;
- (c) surface cooling rates are independent;
- (d) the time pulse profile is constant over the pulse duration;
- (e) the spatial longitudinal profile of heat deposition is either constant, parabolic, or attenuated;
- (f) the spatial radial profile is either constant, Gaussian, or polynomial and it could also be truncated;
- (g) the laser pump can be continuous or pulsed and the pulses could be composed of either single pulses as is found in single frequency laser systems, or a two pulse sequences as is the case in the pump arrangement of two color lidar systems (DIAL); and
- (h) the programs can be run for arbitrary time periods and sampling rates of the on and off periods are specified by the user.

The temperature variations in a Cr:LiSAF crystal was obtained for a continuously end-pumped configuration. The rod is 0.2 cm in length and 0.1 cm in radius. The pump power is 0.095 Watts and the pump has a Gaussian profile whose radius is 50 microns.

Figure 1. compares the initial temperature profile with the final steady state one. The changes in the shape of the profile is a reflection of the diffusion process within the rod. Figure 2. tracks the rise in temperature at the center of the end-pump face. The information provided in both figures is the typical information that is of interest in the design of laser systems.

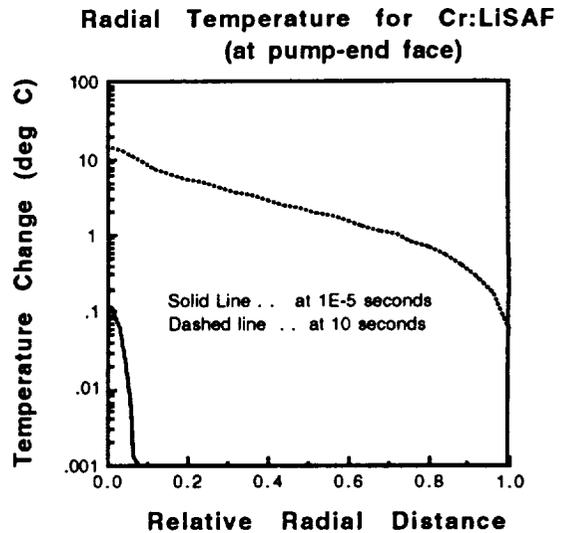


Figure 1. Comparison of initial and final temperature profiles

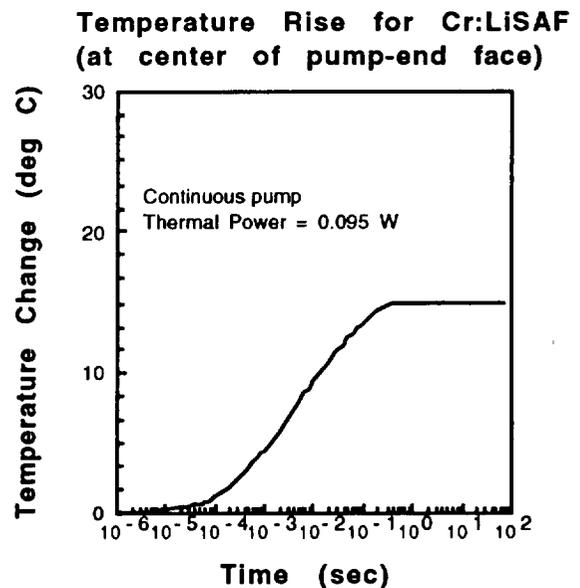


Figure 2. Rise in temperature at the center of the rod.

1992 OBJECTIVES

The previous attempt to find an expression for steady state temperature distribution that does not depend on the eigenfunctions expansions used in the time dependent expressions was not successful. Obtaining an expression for the steady state temperature is impor-

tant for program verification and for obtaining a good estimate of thermally induced birefringence.

Experimental data on temperature distribution could provide such verification whenever available. At the present time the effort is focused on modifying the temperature distribution expressions and the computer program to allow for the case when all the components of thermal conductivity are unequal. Non cylindrical pump beam profiles are also of interest. A graduate student will be involved in the incorporation of stress and strain tensor calculations in this effort.

PUBLICATIONS AND INFORMATION TRANSFER

"Time dependant temperature distribution in end-pumped repetitively pulsed laser rods," Farrukh, Usamah O., and Philip Brockman, submitted to IEEE J. of Quantum Electronics, (1991).

"Temperature distribution in end-pumped laser crystal rods: transient and spatial variations," Farrukh, Usamah O., Norm Barnes, and Philip Brockman, to be submitted to Applied Optics, (1992).

"Transient Temperature Fluctuations in End-Pumped Multi-Pulsed Laser Rods," Farrukh, Usamah O., Marian Clayton, and Brockman, Philip, OSA Annual Meeting, November 7, 1991, San Jose, California.

"Near Field Diffraction and Focusing of Gaussian Beams by Apertured Lenses", Farrukh, Usamah O., OSA annual meeting, November 4, 1991, San Jose, California.

Computer Program: "Computing temperatures in optically pumped laser rods," Farrukh, Usamah O., COSMIC Data Base, The University of Georgia, Athens Georgia, NASA Tech-Briefs, Vol. 15 (7), pp. 63, 1991.

Amplified Spontaneous Emission In Solar-Pumped Iodine Lasers

Principle Investigators : Kwang S. Han & In Heon Hwang

DESCRIPTION OF RESEARCH

The amplified spontaneous emission (ASE) from a long pulse, solar simulating radiation pumped iodine laser is studied. The ASE threshold pump intensity is almost proportional to the inverse of the laser gain length when the gas pressure is constant in the laser tube.

Solar-pumped lasers are under study in many laboratories around the world as futuristic energy sources for in-space and on-ground applications. Among various laser materials, Nd:YAG and some other rare-earth ion doped solid laser materials have been lased with concentrated solar radiation [1, 2, 3]. The solar-pumped iodine gas laser has been studied at NASA Langley Research Center since 1980 [4] for future application in space. Recently, a 30 W CW output power was obtained from a solar simulator pumped CW iodine laser with $i\text{-C}_3\text{F}_7\text{I}$ as the lasing material [5]. A master-oscillator power-amplifier (MOPA) architecture is one of many schemes under study in the center for long distance power beaming [6].

A practical laser system for space application has to be large enough to generate high energy and power for various missions. The length of the laser medium must be long to reduce the threshold pump intensity because of the weak solar spectral power. Reduced threshold pump intensity is required for high total system efficiency [7]. At the same time, the diameter of the laser material should be optimized for uniform pumping. In solar-pumped iodine laser, the product of the tube diameter and the gas pressure is found to be about 50 Torr \cdot cm for $n\text{-C}_3\text{F}_7\text{I}$ from experiment. This value is about one third of

that in short pulse pumped high power iodine laser [8].

One of the most serious problems in the construction of a high-power laser system is the amplified spontaneous emission (ASE) which is also known as the "mirrorless laser" effect. ASE appears frequently in high gain lasers, such as dye lasers [9] or long gain-length lasers [10]. ASE also appears in high gain excimer lasers [11]. The ASE affects the laser performance in various ways. ASE does not only reduce the laser efficiency of an oscillator but also limit the energy storage capability in an amplifier. In this experiment, the ASE threshold pump intensity is measured as a function of the gain length of the iodine laser amplifier for the identification of the parametric criteria in the space-based solar-pumped iodine laser MOPA system.

The laser amplifier system used in this experiment is composed of a 2-m-long amplifier tube and solar simulating flashlamps. The diameter of the amplifier tube is 2.7 cm, and the optimum pressure for uniform pumping was about 15 Torr when $n\text{-C}_3\text{F}_7\text{I}$ was used as the amplifying medium. Therefore all the experimental data were taken with 15 Torr of $n\text{-C}_3\text{F}_7\text{I}$. The reflector-collector system is designed to concentrate only the light reflected once from the reflector and once from the collector into the laser tube, except light direct from the flashlamp to the amplifier tube. This geometry closely simulates the solar-pumped laser amplifier. The solar-simulator in this system is the two 1 m long flashlamps. The flashlamps were powered by two pulse forming networks (PFN) for a long pulse duration. With this pulse forming network, the pumping pulse duration was about 1 msec as shown in Figure 3. The overlapped trapezoidal pulse in Figure 3 is for the model calculation of the population inversion. The pump light from the flashlamps was measured with an optical multichannel analyzer (OMA; Tracor

Northern TN 6500, spectrograph; Jarrell-Ash 82-498, detector head; Tracor Northern TN 6132) very carefully to compare with the air-mass-zero (AMO) solar radiation. The peak spectral irradiance from the solar simulating flashlamp is compared with the AMO solar irradiance and the absorption cross section of the iodide laser material used in the solar pumped laser experiment. When the flashlamps were driven with 8 kV charging voltage in the PFNs, the peak spectral irradiance in the absorption band of the iodides is approximately equal to 4,000 solar constant of AMO sun light as shown in Figure 4.

First, the small signal amplification by this amplifier system was measured with a XeCl laser pumped iodine laser oscillator to determine the population. The iodine laser oscillator generated a 20 nsec long laser pulse with output energy of about 3 mJ in TEM_{00} mode [12]. The laser beam was expanded to fill the whole of the amplifier cross section. The time delay between the amplifier pump pulse and the oscillator output injection into the amplifier is controlled by a delay generator. As shown in Figure 5, the population inversion does not increase noticeably after 0.5 msec from the start of pumping and shows quite a large discrepancy from the model calculation which is developed in this project [6] after 0.5 msec. In this experiment, the peak pumping intensity was equivalent to about 4,500 AMO solar constant. With this experimental result, the population inversion is judged to be depleted seriously after 0.5 msec from the start of pumping at such a high pump intensity. Two reasons for the population depletion were conceived; one is the ASE and the other is the slow formation of the iodine molecule. The ASE is responsible for the early population depletion and the iodine molecule is responsible for the late population depletion.

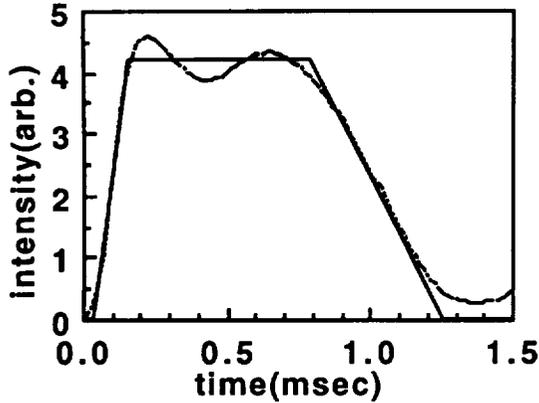


Figure 3. The optical pulse from the solar simulating flashlamp (dotted line). The optical pulse was approximated as a trapezoidal pulse (solid line) for the model calculation of the population inversion.

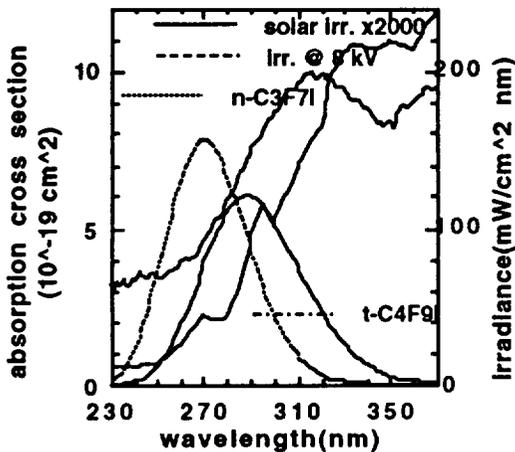


Figure 4. The spectral irradiance from the flashlamp compared with that of the AM0 sun light in the absorption band of the iodides used in solar-pumped iodine laser research.

With this fact in mind, we measured the ASE threshold dependence on the amplifier length. The experimental setup for the ASE threshold measurement is shown in Figure 6. By varying the pumped length of the amplifier tube, the threshold pump intensity was measured for the ASE output. A sensitive Ge photodiode (Jodson J-16LD) was used for the detection of the ASE output.

In this measurement, every glossy material was removed from the axis of the amplifier tube to exclude the possibility of parasitic oscillation. For the measurement at lengths over 200 cm, one full mirror was placed at one end of the amplifier tube. The result of the measurement is shown in Figure 7.

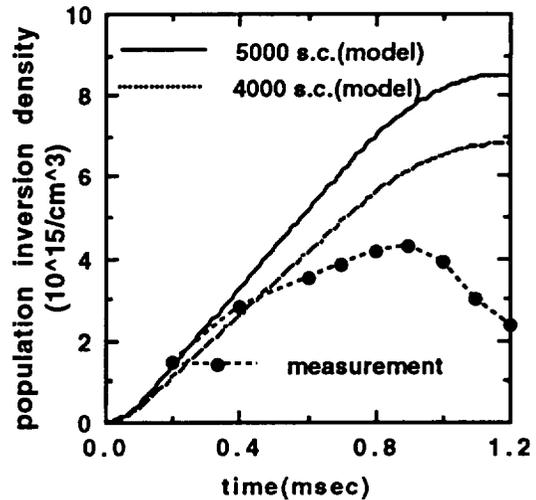


Figure 5. The measured population inversion compared with the model calculation. The pumping intensity in this experiment was equivalent to 4,000 solar constant AM0 sun light.

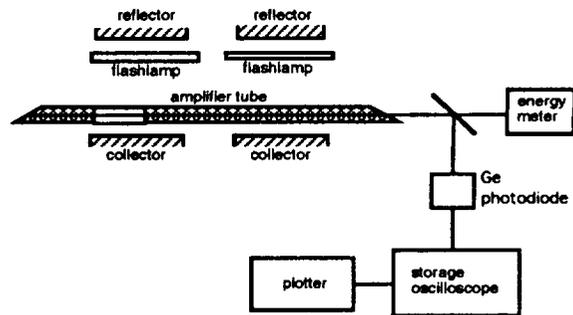


Figure 6. Experimental setup for the measurement of the ASE threshold pump intensity.

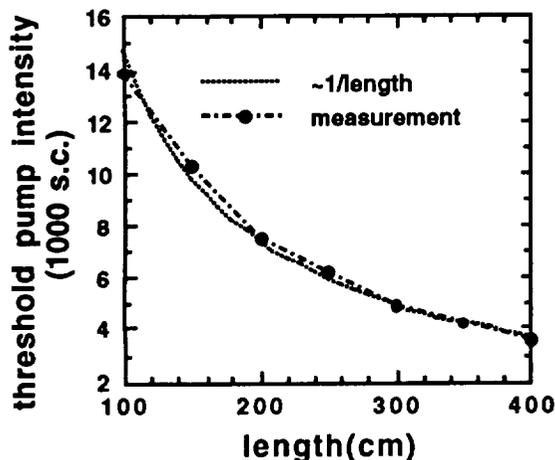


Figure 7. The ASE threshold pump intensity dependence on the pumped amplifier tube length. The experimental data fit generally well with the $1/(\text{gain length})$.

ACCOMPLISHMENTS

As shown in Figure 7, the threshold pump intensity for ASE from the iodine laser amplifier decreases as the gain length increases. The relation between the ASE threshold pump intensity and the length of the amplifier tube shows approximate inverse proportionality. Peters and Allen have derived the relation for the ASE threshold population density and the gain length [13]. The relation by these authors is

$$L\Delta N_{th} = 1/\sigma \quad (1)$$

where L is the length of the amplifying medium, ΔN_{th} is the threshold population inversion density, and σ is the stimulated emission cross section. The stimulated emission cross section of the excited atomic iodine is well determined experimentally by many researchers [8]. The transition between $F=3$ of $2P_{1/2}$ and $F=4$ of $2P_{3/2}$ has the largest stimulated cross section among the 6 transitions. Therefore the ASE threshold may be certainly determined by $F=3$ to $F=4$ transition. The stimulated emission cross section at this transition is about $5.2 \times 10^{-18} \text{ cm}^2$ at the pressure lower than 20 Torr. With

this stimulated emission cross section, the product of the threshold population inversion density and the length is $1.9 \times 10^{17}/\text{cm}^2$. The product of the threshold population inversion density and the gain length is measured as shown in Figure 8 by measuring the time when the ASE occurs. As shown in Figure 8, the product is almost constant for different gain length. However, the product measured in this experiment is almost one order of magnitude larger than that calculated from Eq. (1). The reason for this disagreement is not clear at this moment.

In conclusion, we measured the ASE threshold pump intensity in solar simulating radiation pumped iodine laser amplifier with $n\text{-C}_3\text{F}_7\text{I}$, and found that it is proportional to the inverse of the gain length when the iodide gas pressure in the laser tube is constant. The product of the threshold population inversion density and the gain length is also measured from this experiment and is shown to be constant for different pumping intensity and for different gain length. This fact agrees with the theoretical consideration, but the numerical value is one order of magnitude differ from the theoretical calculation, which is not clarified yet. More elaborated experiment is necessary for the clarification of the discrepancy.

1992 OBJECTIVES

As already discussed, ASE is a troublesome characteristics of a high gain laser. Therefore, there has been serious efforts to reduce the stimulated emission cross section in high power short pulse iodine laser [8]. The most easily adopted method was the addition of inert gas to the iodide gas to broaden the linewidth of the laser transition and eventually to reduce the stimulated emission cross section. However, if inert gas is mixed with the iodide gas, the lifetime in the excited state reduces inversely proportional to the gas pressure. In case of solar-pumped laser

amplifier, the long upper state lifetime is the most required property of the laser material for high energy storage in the laser medium because of the weak pump rate with sun light. Thus the physical dimension of the amplifier should be carefully optimized to avoid the ASE and, at the same time, to maximize the system efficiency.

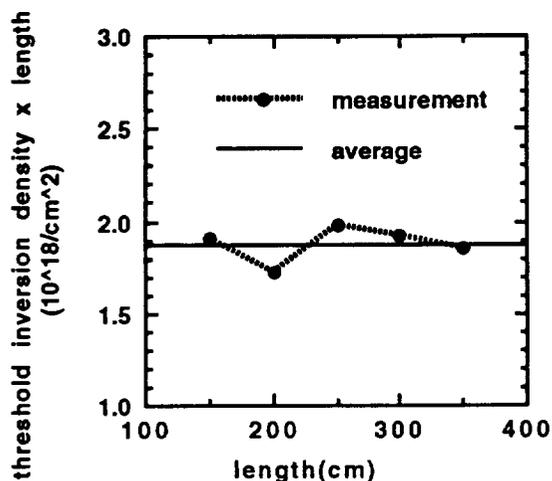


Figure 8 The product of ASE threshold population inversion density and the gain length.

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"Efficiency and threshold pump intensity of CW solar-pumped solid-state lasers", I. H. Hwang and J. H. Lee, *IEEE J. Quantum Electron.* **QE-27**, 2129 - 2134 (1991).

"Amplified spontaneous emission in solar-pumped iodine laser", Y. S. Cho, I. H. Hwang, K. S. Han, and J. H. Lee, presented in the International Conference on Lasers'91, San Diego, CA, Dec. 9 - 13, 1991.

Closely-Simulated AM0 CW Solar-Pumped Iodine Laser and Repeatedly Short-Pulsed Iodine Laser Oscillator

Principal Investigators: Bagher M. Tabibi & Demetrius D. Venable

DESCRIPTION OF RESEARCH

During 1991 research on direct solar-pumped iodine lasers was carried out in two parts: the cw solar simulator argon arc lamp irradiance was modified in order to closely simulate AM0 (air mass zero) sun for pumping of iodides; and a repeatedly operated short-pulsed iodine laser oscillator has been developed. The purpose of the first experiment was to compare the cw laser performances of n-C₃F₇I and t-C₄F₉I. The goal of the second experiment was to achieve a short-pulse high repetition rate iodine laser oscillator as a master oscillator for the power amplifier.

The experiments on direct solar-pumped laser systems for space power transmission are continuing at NASA Langley Research Center and Hampton University. A key element in the choice of a laser system is the efficiency of solar-to-laser energy conversion. High efficiency of one laser system under study, the iodine laser, depends on the availability of a suitable iodide which has favorable laser kinetics, high chemical reversibility, and efficient solar energy utilization. During the previous research period, a closely-simulated AM0 solar-pumped pulse iodine laser system was completed and t-C₄F₉I as a favorable lasant for the solar-pumped iodine laser system was evaluated [14]. However, the operating conditions of a laser medium in a continuously pumped and continuously flowing iodine laser differ considerably from those in the pulsed regime. Therefore, an experiment was conducted to modify the previous cw solar-simulator-pumped iodine laser system [15] in order to closely simulate the AM0

solar spectrum. This progress report describes the results of this modification. The comparative laser performances from n-C₃F₇I and t-C₄F₉I under closely simulated solar pumping are awaiting for the availability of t-C₄F₉I.

Also, during this report period a short-pulse pumped iodine laser oscillator has been developed to form a master-oscillator power-amplifier (MOPA) system. The purpose of MOPA and its advantages are indicated earlier [15]. The system uses a plasma device developed by Lee et al [16], called a hypocycloidal pinch (HCP), which produces intense uv emission and makes a high-power pumping source for iodine lasers [17]. This report also includes the preliminary result obtained from this iodine laser oscillator.

ACCOMPLISHMENTS

Figure 9 shows the experimental set up for the spectral irradiance measurement of the Vortek solar-simulator to compare with the AM0 solar spectrum. The Vortek stabilized argon arc emits a radiant flux of up to 45 kW when applying an electrical input power of up to 100 kW. A 20 cm length arc with 11 mm diameter is produced along a Germal quartz tube of 20 mm diameter and 25 cm length.

To measure the spectral irradiance in the near uv region from 200 nm to 400 nm, a standard deuterium lamp (model uv-40, S/N:600) was used as the calibration reference. The Vortek lamp and standard deuterium lamp were compared directly by a substitution method, i.e. the optical system was kept the same throughout the measurement and only the sources were replaced. The light emitted from the Vortek lamp and reflected from the elliptical cylindrical reflector were coupled into the suprasil laser tube surrounded by a cooled deionized water jacket. A computerized optical multichannel analyzer (OMA)

enabled instant acquisition of the spectrum.

A probe from the copper tube with 20 mm diameter and water cooling which had a 2 mm diameter diffused window was entered into the laser tube. The diffused window faced the inside wall of the laser tube. It could be moved along the laser tube so that the light entering into the laser tube at any point along the axis could be measured. The probe could also be rotated around the axis to face direct light from the lamp or any reflected light from the reflector. The scattered light from the diffused window could be reflected from an aluminum mirror into a uv super-guide silica fiber that directs the light to the slit of the spectrometer. The probe was water cooled without flowing water on the surfaces of the window, mirror or fiber. To avoid the movement of the fiber as the result of the movement of the probe along the tube and its rotation around the axis, both ends of the fiber were fixed by epoxy glue. Since the irradiance of the Vortek lamp was very high, a neutral density filter with known uv transmittance was used on the slit of the spectrometer to attenuate the intensity.

Figure 10 compares the measured irradiance of an unmodified Vortek lamp (only cooled deionized water circulated around the laser tube) with the AM0 solar irradiance normalized at 300 nm. The Vortek lamp irradiance is significantly higher in the uv region, the pumping region of iodides, than that of 52•AM0 solar irradiance. For example, the ratio of the measured unmodified Vortek lamp irradiance at 290 nm (the absorption peak of t-C₄F₉I) and 272 nm (the absorption peak of n-C₃F₇I) is 1.15, while this ratio for the AM0 solar irradiance is 2.36. This motivated the need to modify the Vortek lamp spectrum. We therefore, employed a mixture of acetone and deionized water with a relative concentration of 1:150 (acetone : deionized water) circulated around the laser tube to filter the uv

portion of the Vortek lamp spectrum within the absorption bands of the iodides and thus more closely simulated AM0 solar spectral irradiance.

Figure 11 presents the measured irradiance of the modified Vortek lamp light and AM0 solar irradiance multiplied by a factor of 19. The measured irradiance of the modified Vortek lamp light in the absorption bands of the iodides was 36 % less than that of the unmodified Vortek lamp light for the same electrical input power. This figure gives a value of 2.27 for the ratio of measured Vortek lamp irradiance at 290 nm and 272 nm which is closer to that of 2.36 for the AM0 solar irradiance.

The preliminary result obtained from the repeatedly operation short-pulse iodine laser oscillator was a train of 6 pulses per minute using a flow of 20 Torr $n\text{-C}_3\text{F}_7\text{I}$ and 73 joules electrical input energy. The energy of laser pulse was a few millijoules and its duration $\sim 6 \mu\text{s}$ (FWHM).

1992 OBJECTIVES

The work plans for the continued period are to:

- (a) demonstrate at least 40 watts cw laser power output using $t\text{-C}_4\text{F}_9\text{I}$ as lasant;
- (b) compare the cw laser output from $t\text{-C}_4\text{F}_9\text{I}$ to that of $n\text{-C}_3\text{F}_7\text{I}$ under closely-simulated AM0 solar spectrum;
- (c) demonstrate a closed-cycle operation of cw solar-pumped iodine laser system with $t\text{-C}_4\text{F}_9\text{I}$.

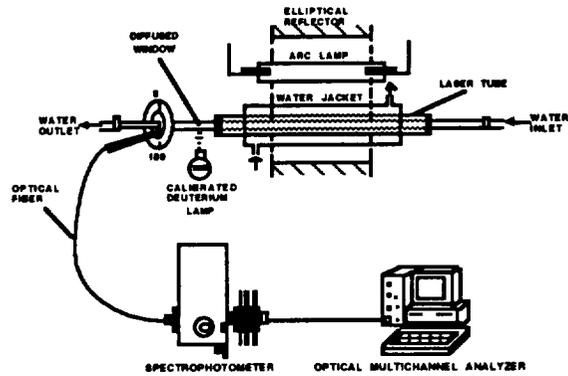


Figure 9. Experimental set-up for spectral irradiance measurement

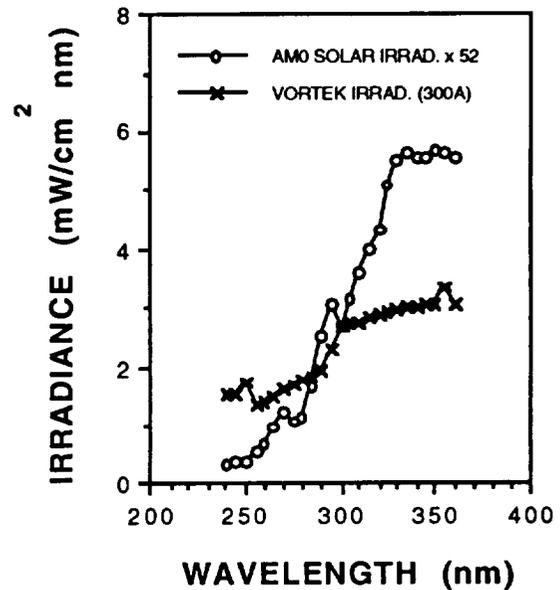


Figure 10. The unmodified Vortex Lamp irradiance and AM0 solar irradiance

PUBLICATIONS AND INFORMATION TRANSFER

Proceeding of the 1991 Annual Meeting of the National Society of Black Physicists and the XVIII Day of Scientific Lectures, edited by Demetrius D. Venable (1992).

"Thermal Effects on Cavity Stability of Chromium- and Neodymium- Doped Gadolinium Scandium Gallium Garnet

Laser Under Solar Simulator Pumping," K. H. Kim, D. D. Venable, L. A. Brown and Ja H. Lee. *Journal of Applied Physics* 89, 2841 (1991).

"Perfluoro-t-butyl Iodide as an Alternate Laser Medium for Solar Pumping in Space," Bagher M. Tabibi, Abdulaziz Gambo, D. D. Venable, and Ja H. Lee. Presented at the Conference on Lasers and Electro Optics (CLEO'91) Baltimore Md., May 1991, May 1991

"Focused Studies in Spaceborne Photonics," Calvin Lowe and D. D. Venable. Presented at the Jet Propulsion Laboratory Third Annual Technical Interchange Workshop, January 22-25, 1991.

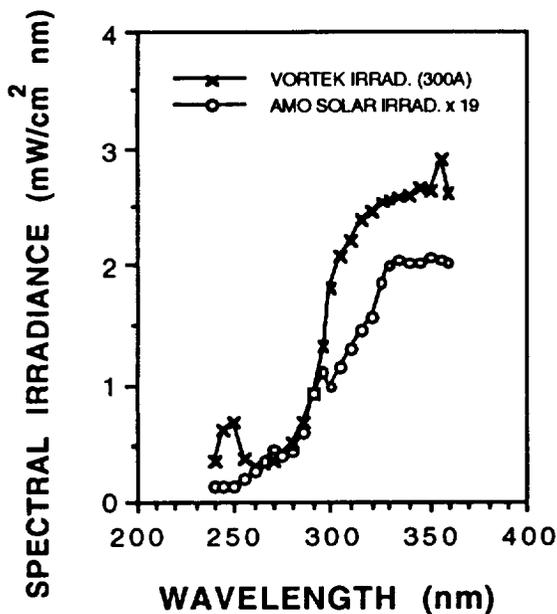


Figure 11. The modified Vortek Lamp irradiance and the AMO solar irradiance

The Materials Spectroscopy and Growth Program

Principal Investigator: C. J. Lee

DESCRIPTION OF RESEARCH

Dr. Calvin Lowe, the former P.I. for this project has left to University to

accept a position elsewhere. Dr. C. J. Lee joined the research team in July and is currently providing the leadership in this area. Dr. D. Yeh, who is currently on the physics department staff is expected to join this group in the near future. Dr. Yeh will serve as the advisor of Dr. Lowe's former students so that they may completed their theses requirements.

The materials growth group that was under Dr. Lowe's direction will continue its current growth and analysis activities [15] until the students complete their projects. After that time these activities are completed will be incorporated within the broader RCOP mission that time. Dr. C. J. Lee's work will be involved with the development of Holmium Laser systems.

ACCOMPLISHMENTS

As a member of the 2.1 μm Holmium laser group in the Flight Electronics Division, C. J. Lee's research objective has been to develop an Alexandrite laser pumped Ho:Tm:YAG or Ho:Tm:YLF 2.1 μm laser system.

The 2.1 μm laser is proposed to be an eye-safe solid-state laser for Doppler Lidar wind velocity/shear measurements and Differential Absorption Lidar (DIAL) trace gas measurements. It is envisioned that the ultimate system will utilize a laser diode array pumping scheme. Since the technology for the high power laser diode arrays is still under development, the Alexandrite laser is an alternative pumping source to study the 2.1 μm laser system with high power laser pumping at diode laser wavelengths. The Alexandrite laser, which operates at the wavelength of 785 nm, pumps the laser crystal longitudinally and excites ground state of Tm to the $^3\text{H}_4$ state. This excited state decays to the $^3\text{F}_4$ manifold through radiative and nonradiative processes. Subsequently the Tm($^3\text{F}_4$) state transfers its excitation energy to the

Ho(5I_7) state followed by Ho(5I_7 - 5I_8) laser emission at 2.1 μm (see Figure 12).

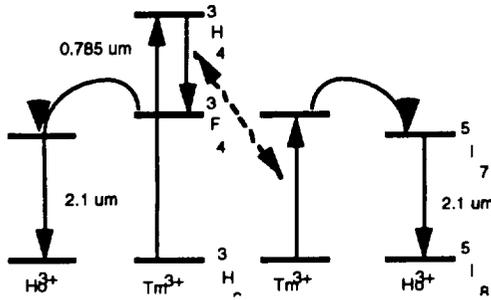


Figure 12. Energy level diagram for Ho-Tm system

1992 OBJECTIVES

There are several energy transfers which effect the optimum laser design parameters such as sensitizer (Tm) and activator (Ho) concentrations, temperature of the laser crystal, etc. The purpose of this experiment is to understand these energy transfer mechanisms.

The following subjects will be studied within 1992.

- (a) Spectroscopy
- (b) Threshold
- (c) Slope Efficiency
- (d) Laser Output Power
- (e) Q-switching
- (f) Temperature Dependence (down to about 150 K).

Performing gain measurements and developing power oscillators are being considered for long term additions to the above items.

PUBLICATIONS AND INFORMATION TRANSFER

"Remote Control Using LIDAR", C. J. Lee, Invited talk Yeungnam University, December 16, 1991.

"Laser Spectroscopy of Molecular LiNe", C. J. Lee, Invited talk

Kyungbuk National University December 18, 1991.

Laser Induced Fluorescence and Atomic and Molecular Spectroscopy

Principal Investigators: Nelson Jalufka and K. S. Han

DESCRIPTION OF RESEARCH

This research supports NASA's Space Power Transmission and solar pumped iodine laser program. In the last reporting period work has been concentrated on laboratory studies of quenching of I^* by the parent molecule $t\text{-C}_4\text{F}_9\text{I}$.

The iodine laser operates on the photodissociation of a perfluoroalkyl iodide (RI) to produce excited iodine atoms (I^*). Lasing occurs on the magnetic dipole transition $2P_{1/2} \rightarrow 2P_{3/2}$ at a wavelength of 1.3152 μm . Several reactions occur which affect the performance of the more important of these processes in the quenching of the excited iodine atom (I^*) by the parent molecule RI.

Transmission of power in space is of interest to NASA as this is one means of providing power to spacecraft and to permanent facilities in space such as a lunar station. It is anticipated that a pulse laser with high average power will be used as the transmitter. Conversion of the laser power to electrical power will be accomplished by use of solid state power converters similar to solar cells. At this time it is not known how the use of a pulsed rather than a cw laser will affect the performance of the converters.

ACCOMPLISHMENTS

During 1991 the system for measurement of radiation lifetime was assembled. This system (Figure 13) consist of the following.

1. XeCl Excimer laser having a pulse energy of 50 mj per pulse width of about 10 nanoseconds. The laser operates at 308 nanometers which is well within the absorption of t-C₄F₉I. The laser pulse producer I* by photodissociation of the C₄F₉I.
2. Quartz cell vacuum system which is used to evacuate the cell and then fill it to a specified density of the iodide and a buffer gas if required.
3. Germanium detector/filter combination which detects the I* radiation decay through a 1.315 μm filter. The output of the detector is amplified and recorded on an oscilloscope with averaging capabilities. For each pressure minimum of 500 pulses are averaged for each data point .
4. By averaging the pressure a set of data is obtained which is analyzed by a Stern-Vollmer method. This procedure allows the recovery of the quenching rate from the analysis.

The system is presently in operation and producing data although some difficulty is encountered with extraneous radiation. We are presently working to eliminate the sources of extraneous radiation.

Research to investigate the characteristics of Si and GaAs converters where irradiated by a pulsed light source (laser) was initiated in this reporting period. These solid state devices have been used for a number years and their characteristics when irradiated by a continuous source are well known. However, their behavior when irradiated by a pulsed light source has not been investigated. In this experiment (Figure 14) a pulsed dye laser (0.34 μJ and approximately 1 ps pulse

width) is used to irradiate the solid state converters conversion efficiency as a function of load resistor has been carried out for radiation at 600 nm. Several parameters will be varied in this experiment including:

1. Laser pulse width,
2. Laser pulse power,
3. Laser wavelength, and
4. Pulse repetition rate.

When the laser photon energy is close to the converter energy band gap high conversion efficiency is expected. Initial measurements carried out in 1991 indicate that conversion efficiency in excess of 50% are obtainable.

1992 OBJECTIVES

During 1992 we anticipate the completion of the quenching rate measurement of I* by t-C₄F₉I This research will provide the necessary material for a Master's Thesis for one student.

More effort will be devoted to the measurements of solid state laser converters response to pulsed laser radiation. It is anticipated that these measurements will be completed in 1992 and will provide the necessary material for a Master's Thesis for one student.

A new research effort will be undertaken in conjunction with Dr R. DeYoung of NASA Langley Research Center. This research will be directed toward the development of a remote sensing system for space application.

The system will consist of a NdYAG pulsed laser, a time-of flight mass spectrometer, optical spectroscopy instrumentation and the necessary vacuum vessels and pumps. The system will be used in the following way:

1. The laser, at a distance of 10 meters from the sample, will be used to create a high temperature plasma from the sample material.
2. Particles (atoms, molecules etc.) which are energetically ejected from the plasma will be detected by the mass spectrometer which will be located adjacent to the laser.
3. Confirmation of the species ejected by the plasma will be by optical spectroscopy.
4. If the concept proves feasible many applications such as remote chemical analysis of asteroids, surface analysis of other planets and remote sensing of Terrestrial location become apparent.

One graduate student will work on the development of this system for a Master's Thesis research project.

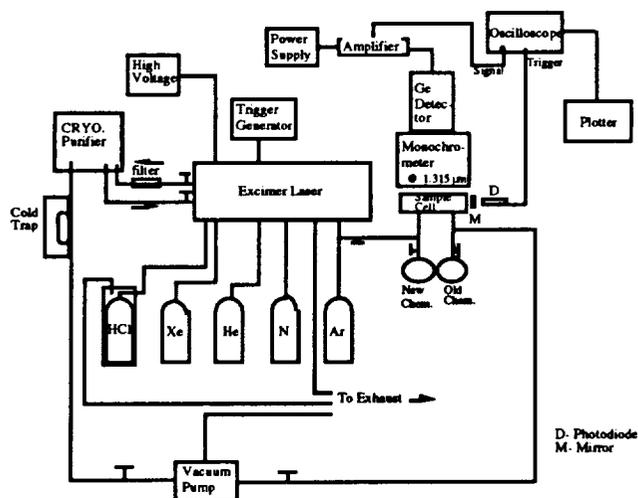


Fig. 13 Experimental setup of lifetime measurement of excited iodine atoms in per-fluoroalkyl iodide research.

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Vibrational Relaxation of Bismuth", S. Jang, and N. Jalufka, Virginia Academy of Science Annual Meeting, Blacksburg, VA, 1991

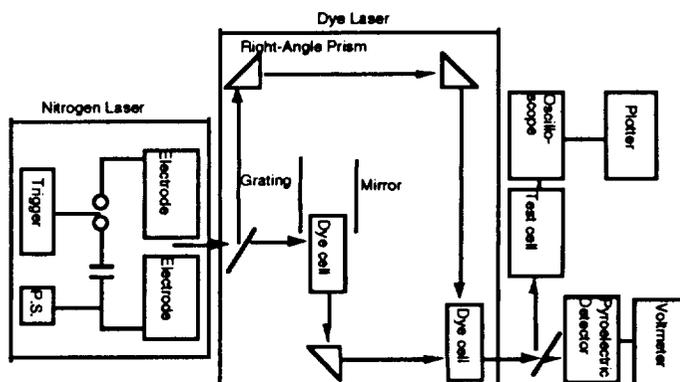


Fig. 14. Block diagram of experimental arrangement.

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Appendices